Prediction of firefighting resources
for suppression operations
in Victoria's parks and forests

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Summary

Estimating resourcing levels for park and forest firefighting is a perennial challenge for wildland fire managers. Low numbers of resources during first attack often achieve significant results if fires are caught in the build-up phase. Conversely, during campaign fires, large numbers of resources occasionally appear to under-achieve, with little obvious result in terms of length of fireline constructed despite significant resource inputs.

Previous predictions of fireline construction rates in Victoria relied mainly on the experience of Incident Planners and more formally on information derived from studies in USA and Canada. Some information has been based on local trials and demonstrations but most of these were decades old and of variable reliability.

The 1980's national bushfire research project—Project Aquarius—provided some information on hand trail construction rates but there has subsequently been some speculation on how these may relate to actual fireline situations.

This project was therefore directed towards collecting information on firefighting resource allocation and fireline construction rates achieved in recent actual fire events, with the aim of producing models based on real, and current operational data.

Data on fireline conditions and fireline construction rates were collected from 103 fire events spanning the 1997–98 to 2000–01 fire seasons in Victoria. Models of fireline construction rates for hand trail, small bulldozers and large bulldozers were developed based on this data. Some information was also collected in regard to holding rates of 'wet lines' using both ground-based tankers and firebombers. Preliminary data on critical resource combinations for containment of various lengths of fireline was also collected.

Hand trail construction rates, based on actual fireline data, appeared to be considerably lower than those obtained in the past from demonstration-type situations (e.g. Project Aquarius). The main factors influencing the variation in these construction rates were found to be elevated fuel and terrain class, with average rates (90–120 m/crew/hour) declining quickly when the six-person crew was faced with substantial elevated fuels and/or steep, broken terrain (down to 30–60 m/crew/hour).

The main factors influencing construction rates for smaller bulldozers were found to be terrain, debris and operator experience. Operator experience was slightly less important for larger bulldozers, with terrain, debris and rock being the major influencing factors.

Resource combinations were not studied in detail, but some combinations which had been found to be successful for containment over a range of fireline lengths and conditions were suggested as the basis for minimum resourcing.

Over- and under-resourcing were also briefly considered and found to be fairly uncommon.

The models derived from the data have been used to develop a firefighting resources guide for park and forest fire managers (Appendix).

Introduction

Matching firefighting resources with the suppression task at hand has always been a dilemma for the wildland fire manager. Resources have often been insufficient in the early phases of a fire, while later on there has often been an "embarrassment of riches", with the fire manager struggling to find useful work for an over-supply of firefighters and appliances.

While many fire managers have learned through experience to judge the right level of resources to allocate to any particular fire-fighting task, there have never been specialised predictive tools in the Australian context to assist with this task. The complications also often increased markedly with increasing fire size. There was an increasing need for the tools to judge the numbers of firefighters and amount of equipment sufficient for the task at hand. Over-ordering was always a temptation, especially early in a fire campaign, when the size of the task ahead was not clear.

Guides to fireline construction rates for various resources have been available from USA and Canada, but their applicability to Australian resources, topography, vegetation and fire situations was limited.

The major fire event for the 1997–98 Victorian fire season, the 10-day, 35 000-ha Caledonia fire (Heyfield Fire 031) in the alpine and sub-alpine country in eastern Victoria, posed typical problems in terms of resourcing. Both the terrain and the land tenure (national park) meant that substantial amounts of hand trail needed to be constructed. Much of this hand trail was in steep, rocky country that taxed the abilities of even the best firefighters. While fire planners were concerned as to why rakehoe crews seemed unable to achieve line construction rates in relation to their numbers, the rakehoe crew leaders returned from highly frustrating days where walking (or sometimes sliding) through the terrain was so difficult, that to actually achieve any useful line construction became a secondary objective.

As a consequence, many of the hand trails in the Caledonia fire required large numbers of firefighters over four or five shifts to achieve the desired result. Line construction rates of only 2–5 metres per person per hour were common; well below the expected rate when fire planners proposed some of the sections of hand trail.

This fire event and a number of other situations where suppression crews were frustrated by steep, broken topography or excessively thick fuel complexes, lead to the recognition that a resource allocation guide was needed to assist fire managers make decisions about the appropriate level of resources required for a given set of conditions of fuel, weather, topography and fire size.

Bulldozer construction rates also required investigation, given that the only extant published information related to mostly overseas research. The Department of Sustainability and Environment (the Department) and its predecessors have a long history in the use of smaller bulldozers (Caterpillar D3/D4 or equivalent) and yet little information had been published on how effective this class of machine was across a range of fuel and topographic conditions.

Larger bulldozers, particularly privately-owned machines working on contract, have also become a more common resource at major fire events. There was also a need to evaluate these in relation to achievements under real fireline conditions.

The aims of this project were therefore:

1. To investigate fireline construction rates by both people and machinery under actual fireline conditions.
2. To find out what individual resources, or combinations of resources, were required to achieve control under a variety of fireline conditions.

From the data obtained, it was also intended to develop a guide to construction rates, which would provide a useful tool for fire planners. The resultant guide is provided as an Appendix.

Methods

Selection of fires

A total of 103 fire events were selected for study, principally from the four fire seasons spanning 1997–98 to 2000–01, for two main reasons:

A. Data collection relied mainly on interviews with relevant fire-control staff, accordingly the most recent fires were considered to be the freshest in people's memories and therefore the data would be the most reliable.

B. There was a need to deal with suppression situations that used the most recent types of fire-fighting resources. Resources such as specialised wheeled tractors for desert fires, bobcats for northern flat-country fires and heavy helicopters for urban interface fires have recently expanded fire managers' suppression resource options.

While the limited use of some of these newer items of equipment may not have allowed for modelling of construction rates, their availability and utility to the fire manager needed to be reported.

Data collected for each fire

Data for a range of variables were collected for each fire as follows:

Fuel hazard

The three individual components of fuel hazard - surface fine fuel, bark and elevated - were assessed for the final control line. Fuel hazard, both component and Overall, was assessed using the Overall Fuel Hazard Guide (McCarthy et al. 1999).

Weather

Air temperature, relative humidity and wind direction and speed at the time were collected for the final control line or for the sector of the fire appropriate for the particular set of resourcing data. Where local records were not available, those from the nearest Bureau of Meteorology Automatic Weather Station (AWS) were used. Some interpolation of values was undertaken where the fire site differed substantially in altitude from the AWS site. These weather variables were then used to calculate the Forest Fire Danger Index.

Site and topography

Slope and aspect were assessed at each site where resourcing data was collected. Rockiness and debris were also assessed according to the following numerical rating:

Rockiness	1 = none	2 = 4WD	3 = D4	4 = untrafficable
Debris	1 = none	2 = D4	3 = D6	4 = untrafficable

Fire behaviour

Forward rate of spread (FROS), flame height and spotting distance were recorded as primary measures of fire behaviour for each site where resourcing data was collected. Where appropriate, final perimeter and area of the fire were also recorded. Where the data related to only one section of fire perimeter, the fire behaviour for that specific section was recorded. Except for the few instances when fire research or other fire situation staff were able to measure fire behaviour precisely, most of the information derived from the best estimate of the person on the fireline at the time.

Resources

The total firefighting resources, including all firefighters, vehicles, plant and aircraft were recorded for the fire (or particular section of fireline).

For the sections or sectors of the fire where specific construction or holding rate information was collected, the specific resources which achieved these construction or holding rates were recorded.

Construction rates

The following principles were applied when collecting the data:

Fireline construction rate: the term 'construction' applied when a firefighting crew was hand trailing or a bulldozer or wheeled tractor was constructing a fireline down to mineral earth for the purposes of containing a fire. The rate represents the time taken to construct the line without the immediate influence of fire. The effects on construction rates of active fire near the fireline are addressed in the analysis of the individual construction methods.

All the data on construction rates came from actual fire situations, where the clear intentions of the constructing crews (hand and machine) were to both construct and hold the fire—using the line constructed. However, most of the data collected was about "How long did it take to construct x amount of handtrail or dozer line, using y amounts of firefighters or machines?" Thus, the stated construction rates mostly reflect straightforward construction only, but with the understanding that it may have been necessary for follow-up resources to assist with holding or maintaining the constructed line. The amounts of follow-up resources were not tallied.

Also, particularly in the case of the handtrail construction rates, and over the longer lengths of line constructed, the crew leader may have tasked some of the initial construction crew to 'drop off' and patrol the already constructed line to ensure that it was not breached. Again, this use of resources was not tallied, but may be part of the overall task required, depending on fuels, fire behaviour and spotting activity.

Fireline holding rate: the term 'holding' applied to any method of knocking down active flames other than by constructing a fireline to mineral earth. It was recorded where the only initial attack method was with water or fire retardant which was not backed up immediately by a mineral earth fireline. All line work with tankers and aircraft was therefore recorded as holding rates on the assumption that this activity was generally followed up with the construction of a mineral-earth break. Although this was not always the case, it was applied for data consistency.

Adequacy of resources

Fire managers were asked to evaluate the adequacy of the resources for the task at hand. Where the resources were not adequate, they were asked to rate (from 0–100%) how much of the task the available resources were capable of coping with.

Limitations to operation

Limitations to the operations of both firefighters and machines were recorded on a percentage basis, with the aim of assessing the degree of limitation compared with the situation where no limitations of the particular type existed. That is, for instance, fire managers or machine operators were asked "How much did the terrain limit/reduce the rate of line construction compared to terrain which would present virtually no limitation?"

The degrees of limitation were sorted and recorded in classes as:

Class	Limitation	Degree of limitation (%)
1	construction rate not affected significantly	0
2	present but construction rate slowed only a little	10–20
3	present and construction rate slowed significantly	20–40
4	a major influence and construction rate slowed markedly	50–90

For machines, the limitations investigated were terrain (mainly slope but also position in the terrain, terrain dissection and slope variation), rocks and debris (both dead and live material). The limitations to the operations of firefighters were terrain (mainly slope but also position in the terrain, slope variation and ground surface conditions), rocks, debris (predominantly dead logs and branches) and elevated fuel (live and dead shrub material).

Experience and fitness

Fire managers were asked to rate on a percentage basis (0–100%) the levels of experience of the firefighting crew and machine operator and the fitness of the firefighting crew. The ratings were attributed to four classes that were then expressed as a proportion (0–1) in the results (Table 1).

Experience of the firefighting crew and machine operator was evaluated and classified as:

Class	Experience
1	little experience
2	1–5 fires attended
3	20 or more fires attended
4	100+ fires attended

The fitness of the firefighting crew was assessed and classified as:

Class	Fitness
1	very high fitness (including daily aerobic exercise and strenuous work activity for most of the week - generally Rappell Crews only)
2	high fitness (age less than 30 and engaged in relatively strenuous work for most of the working week - mainly the younger PFFs)
3	average fitness (age 30+ and involved in relatively strenuous work for less than half the week - older PFFs and regular crew)
4	moderate fitness (age 30+ and not involved in any regular strenuous work)

Contribution of aircraft to the suppression effort

The contribution of aircraft was assessed in relation to the following questions:

1) Was aircraft support critical for the suppression operation? (That is, could the suppression operation have been completed in a reasonable time without the use of aircraft?)

2) Did the aircraft assist with suppression? (That is, in situations where containment was achieved by a combination of ground and aircraft resources, how much [0–100%] of the fire containment task was achieved by the aircraft involved?)

3) Did the aircraft save time? How much? (That is, give an estimate of how much extra time might have been involved in containing the fire, if containment had to be achieved without the use of aircraft.)

Overall resourcing

Two questions were asked:

1) Which extra resources (firefighters, tankers, aircraft, machines, other) would have improved or hastened the suppression operation?

2) Were you sent more resources than were required for the suppression operation?

Fire managers were also asked to make any general observations about the resourcing aspect of the suppression operation. This anecdotal information was collected to form the basis for any additional recommendations on resourcing that may not otherwise come out of the statistical analysis of the numerical data.

Statistical analysis

Numerical data that displayed variation were analysed using stepwise multiple regression procedures. Non-linear estimation procedures were used for all categorical data and some numerical variables.

Results

Table 1   All data variables collected with their means, minimum and maximum values and standard deviations for the current data set

Variable	No.	Mean	Minimum	Maximum	Std.Dev.
Weather					
Air Temp (^{0}C)	103	27.8	15	41	5.0
Relative humidity (%)	103	33.3	10	90	14
Windspeed at 2 m height in vegetation at fire site (km/hr)	103	10.5	0	50	10.2
Wind direction (deg)	103	170	0	360	131
Forest Fire Danger Index (FDI)	103	15	2	50	8.8
Fuel hazard					
Surface Fine Fuel Hazard Score	103	3.0	2.0	4.5	0.5
Bark Fuel Hazard Score	103	3.1	1.0	5	0.9
Elevated Fuel Hazard Score	103	3.5	2.0	5	0.9
Overall Fuel Hazard Score	103	3.8	2.5	5	0.7
Fire size and perimeter					
Final fire size[1] (ha)	79	55	0	1319	211
Final fire perimeter (or line length) (m)	103	1986	0	10000	2260
Topography					
Ridgetop (proportion 0–1)	103	0.2	0	1	0.4
Flat ground (proportion 0–1)	103	0.5	0	1	1.1
Slope (deg)	103	11.1	0	40	12.8
Aspect (deg)	99	125	0	360	126
Rock and debris					
Rock score (1–4)	103	1.9	1	4	1.1
Debris score (1–4)	103	2.1	1	4	0.8
Total resources					
Firefighters - NRE (no.)	103	12.9	0	60	15.2
Firefighters - other (no.)	103	5.0	0	100	15.8
D4-sized bulldozer (no.)	103	0.5	0	2	0.5
D6-sized bulldozer (no.)	103	0.5	0	3	0.8
Wheeled tractor - large (no.)	103	0.1	0	2	0.3
Wheeled tractor - small (no.)	103	0.1	0	1	0.2
Aircraft - reconnaissance (no.)	103	0.25	0	2	0.5
Aircraft - fixed-wing firebomber (no.)	103	0.3	0	3	0.7

Note 1: Fire size relates to the section of the fireline studied, not necessarily total size of fire

Table 1 (cont.) All data variables collected with their means, minimum and maximum values and standard deviations for the current data set

Variable	No.	Mean	Minimum	Maximum	Std.Dev.
Total resources (cont.)					
Aircraft - medium helicopter	103	0.2	0	2	0.4
Slip-on units (400 L) (no.)	103	2.2	0	13	2.9
Tankers - NRE (4000 L) no.)	103	0.7	0	6	1
Tankers - other (4000 L) (no.)	103	1.1	0	20	3.1
Fire behaviour					
Flame height (m)	103	1.1	0	5	1
Forward rate of spread (m/hr)	103	144	0	1500	223
Spotting (m)	103	6.7	0	300	32.5
Times[2]					
Starting time for fire event	100	10:45	00:00	23:00	728
Starting time for suppression activity	101	14:20	00:15	24:15	573
Finish time for suppression activity for containment	100	19:00	01:20	34:00	689
Distance walked by dozer to get to fireline (m)	15	3100	0	11000	4025
Time for dozer to get to fireline (hrs)	15	2.2	0	7	1.8
Time for hand trail crew to get to fireline (hrs)	6	1.2	0	3	0.9
Access to perimeter					
Proportion of perimeter accessible to bulldozers	103	0.8	0	1	0.4
Proportion of perimeter accessible to hand trail crews	103	0.96	0	1	0.2
Bulldozer and tractor line construction					
D4-sized bulldozers contributing to construction rate (no.)	29	1	0	1	0
D4 construction rate (m/hr)	29	505	150	1200	298
General experience of D4 operator (proportion 0–1)	29	0.81	0.05	1	0.25
Small wheeled tractors contributing to construction rate (no.)	6	1	1	1	0
Small wheeled tractor construction rate (m/hr)	6	867	500	1800	468
Large wheeled tractors contributing to construction rate (no.)	5	1.2	1	2	0.4
Large wheeled tractor construction rate (m/hr)	5	920	400	2000	653

Note 2:   Times beyond 24:00 hrs are expressed as, for example 24:00 + 10:00 = 34:00

Table 1 (cont.) All data variables collected with their means, minimum and maximum values and standard deviations for the current data set

Variable	No.	Mean	Minimum	Maximum	Std.Dev.
Bulldozer and tractor line construction (cont.)					
D6-sized bulldozers contributing to construction rate (no.)	16	1.1	1	2	0.4
D6-sized bulldozer construction rate (m/hr)	16	640	200	1200	291
D6 operator general experience level (proportion 0–1):	15	0.6	0	0.9	0.3
D7-sized bulldozers contributing to construction rate (no.)	9	1	1	1	0
D7-sized bulldozer construction rate (m/hr)	9	570	250	1000	376
D7 operator general experience level (proportion 0–1)	9	0.7	0.1	0.9	0.24
D9-sized bulldozers contributing to construction rate (no.)	7	1.14	1	2	0.4
D9-sized bulldozer construction rate (m/hr)	7	560	250	840	183
D9 operator general experience level (proportion 0–1, converted from classes)	7	0.5	0.3	0.9	0.3
Hand trail construction					
Firefighters contributing to construction rate (no.)	34	13.7	5	60	12.3
Firefighter construction rate (m/person/hr)	34	17.3	0	44	8.1
Firefighter experience level (0–1, based on classes)	34	0.8	0.1	1	0.2
Firefighter fitness level (0–1, based on classes)	34	0.85	0.6	0.95	0.1
Firebomber and tanker holding rates					
Firebombers contributing to holding rate (no.)	8	1.6	1	4	0.6
Firebomber holding rate (m/hr)	8	165	80	300	55
Tankers contributing to holding rate (no.)	5	2.8	1	4	1.3
Tanker holding rate (m/hr)	5	360	100	800	300
Adjacent active fire					
Amount of fireline constructed with adjacent active fire (proportion 0–1)	67	0.7	0	1	12.1
Adequacy of resources					
Adequacy of resources compared to the task at hand (proportion 0–1)	103	0.8	0.1	1	0.2

Table 1 (cont.) All data variables collected with their means, minimum and maximum values and standard deviations for the current data set

Variable	No.	Mean	Minimum	Maximum	Std.Dev.
Restrictions to bulldozer and tractor line construction rates					
Restriction imposed by terrain (proportion -1–+1, as assessed by operator)	66	0.1	-0.8	0.9	0.2
Restriction imposed by rock (proportion 0–1, as assessed by operator)	66	0.04	0	0.8	0.1
Restriction imposed by live/dead debris (proportion 0–1, as assessed by operator)	66	0.33	0	0.9	0.3
Proportion of dozer line which required to be sidecut (%)	5	0.2	0.05	1.0	0.4
Restrictions to firefighter hand trail construction rates					
Restriction imposed by terrain (proportion 0–1)	34	0.34	0	1.0	0.3
Restriction imposed by rock (proportion 0–1)	34	0.3	0	1.0	0.3
Restriction imposed by dead debris (proportion 0–1)	34	0.25	0	0.8	0.25
Restriction imposed by elevated fuel (proportion 0–1)	34	0.25	0	0.95	0.3
Aircraft contribution to suppression					
Aircraft assisted with suppression (proportion 0–1)	103	0.2	0	1	0.3
Aircraft critical to containment effort (proportion 0–1)	103	0.4	0	1	0.5
Aircraft saved time for containment (proportion 0–1)	49	0.5	0	1	0.5
Estimate of amount of time saved (hrs)	49	1.8	0	12	2.9
Estimate of time saved where aircraft considered critical to containment effort (hours)	49	4.5	0	12	3.6
Requirements for extra resources					
Firefighters (no.)	103	0.7	0	20	3.2
Tankers (no.)	103	0.5	0	5	1.3
Aircraft (no.)	103	0.01	0	2	0.2
D4 bulldozers (no.)	103	0.1	0	1	0.2
D6+ bulldozers (no.)	103	0.2	0	2	0.4
Other resources (no.)	103	0.1	0	1	10.2

Table 1 (cont.) All data variables collected with their means, minimum and maximum values and standard deviations for the current data set

Variable	No.	Mean	Minimum	Maximum	Std.Dev.
Resources surplus to that required for suppression					
Firefighters (no.)	103	0.2	0	10	1.2
Tankers - NRE (no.)	103	0.0	0	4	0.4
Tankers - Country Fire Authority (no.)	103	0.2	0	10	1.3
Aircraft (no.)	103	0.0	0	0	0.0
Bulldozers (no.)	103	0.0	0	0	0.0
Other resources (no.)	103	0.0	0	0	0.0
Machine operator experience and competency					
Operator experience overall (yrs)	47	19	0	35	11
Operator experience in the fire terrain and vegetation (yrs)	47	13.8	0	30	10.2
Supervision requirement (proportion 0–1, converted from classes)	47	0.2	0	1	0.2
Operator understanding of firefighting (proportion 0–1, converted from classes)	47	0.8	0.1	1	0.2
Machine suitability and equipment					
Bulldozer suitability (size) for task required (proportion 0–1, converted from classes)	47	0.8	0.2	1	0.2
Bulldozer equipped with winch (0/1)	47	0.5	0	1	0.5
Bulldozer equipped with angle and tilt blade (0/1)	47	0.4	0	1	0.5
Bulldozer equipped with lights (0/1)	47	0.9	0	1	0.3
Bulldozer equipped with treepusher (0/1)	47	0.2	0	1	0.4
Contract bulldozer (0/1)	47	0.5	0	1	0.5

Data spread by construction or holding method

Figure 1 displays the total number of cases of each fireline construction or holding method which have contributed to the models constructed and shows that there were insufficient data points to conduct valid statistical analyses for:

- small or large wheeled tractors
- firebombers
- tankers.

Figure 1   Number of cases of fireline construction or holding method for the data set
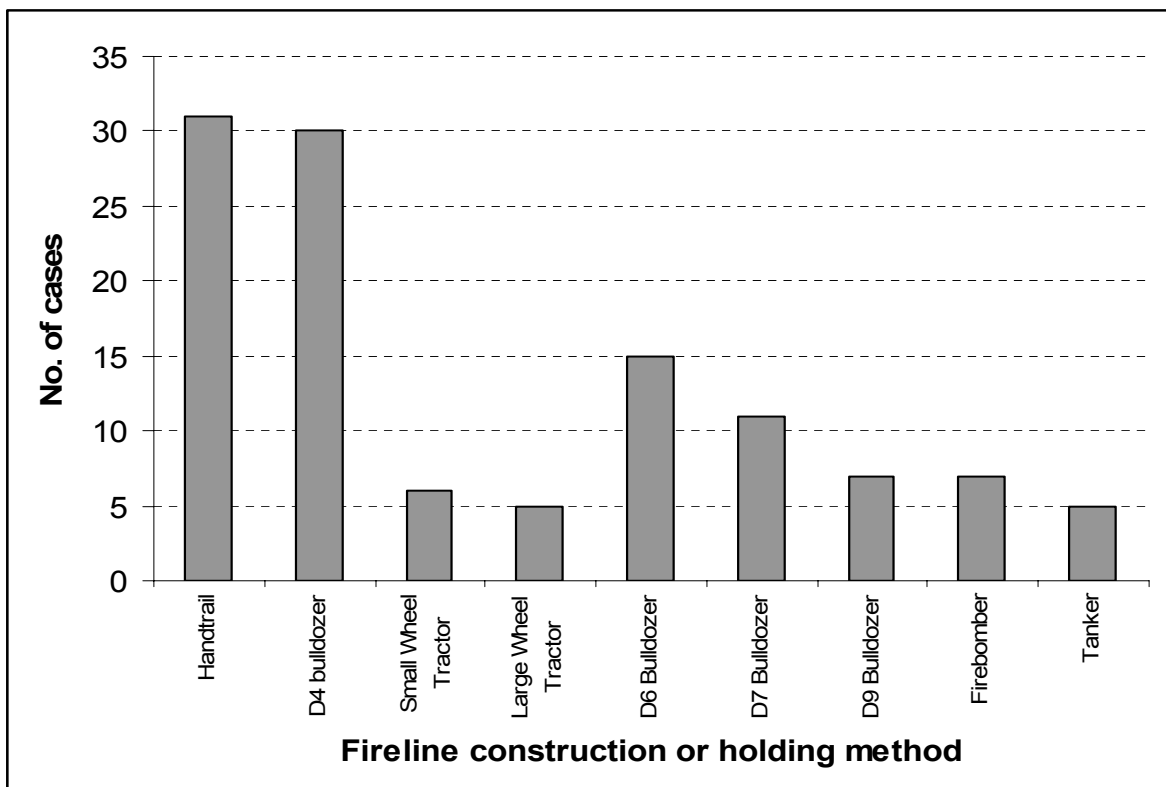
With only 15 observations, the detailed statistical analysis and modelling for D6 bulldozers is of only marginal use. It was modelled because it showed some useful trends in the data. The combined data and modelling for all large bulldozers (D6, D7 and D9), with 33 observations, is statistically more robust.

Table 2   Fireline construction rate summary

Fireline construction method	Average rate	Range of rates	Main factors contributing to variation in construction rate
Hand trail	17 m/person/hr	7.5–44 m/person/hr	Presence of elevated fuel
			Steeper terrain
			Whether working near active flame
			Firefighter fitness
D4-sized machine	350 m/hr	200–1200 m/hr	Presence of adverse terrain
			Presence of significant debris
			Operator experience
D6-sized machine	800 m/hr	300–1000 m/hr	Presence of debris
			Presence of rock
			Operator experience
*D7-sized machine	725 m/hr	250–1000 m/hr	Presence of adverse terrain
			Presence of debris
			% of sidecut
*D9-sized machine	560 m/hr	250–840 m/hr	Presence of adverse terrain
			Presence of debris
			Operator experience
All D6+ machines	700 m/hr	250–1000 m/hr	Presence of debris
			Presence of adverse terrain
			Presence of rock
			Operator experience

* very limited data set available

Table 3   Fireline holding rate summary

Fireline holding method	Average rate	Range of rates	Main factors contributing to variation in holding rate
Tanker	350 m/hr	100–800 m/hr	Wind Speed
			Fuel Hazard
Firebomber	170 m/hr	80–300 m/hr	Presence of debris (live/dead)
			Wind Speed

These holding rates are based on very limited data, and should be treated very cautiously. The factors contributing to variation in holding rates were generally not statistically significant.

Fireline construction rate models

The following models are based on multiple linear regression and non-linear regression analysis of the data.

Firefighter line construction rates

Figure 2 is a two-factor model showing a prediction of line construction rates based on the restrictions on construction imposed by elevated fuel on the fireline and steeper terrain. It shows that most crews should be able to construct about 20–25 metres per person per hour (m/person/hr) in open surface fuels on flatter ground, dropping to less than 5 m/person/hr where substantial elevated fuels and steeper terrain restrict construction. In addition, these modelled rates are based on construction rates obtained over day-length (or longer) shifts and should thereby be valid for a complete shift rather than a shorter period.

The equation describing the model in Figure 2 is:

FFrate = 24.7 + ((-11.4)*FFterr) + ((-14.0)*FFelev)   **Equation 1**

$$(n=34, r^2=0.49, p<001)$$

Where:

      FFrate = Firefighter rate of line construction (m/person/hr)

      FFterr = restriction on firefighters due to the presence of adverse terrain, mostly   (refer Footnote
slope[3]   3 next page)

      FFelev = restriction on firefighters due to the presence of elevated fuel

Figure 2   Model of firefighter line construction rates based on restriction due to the presence of elevated fuel and terrain
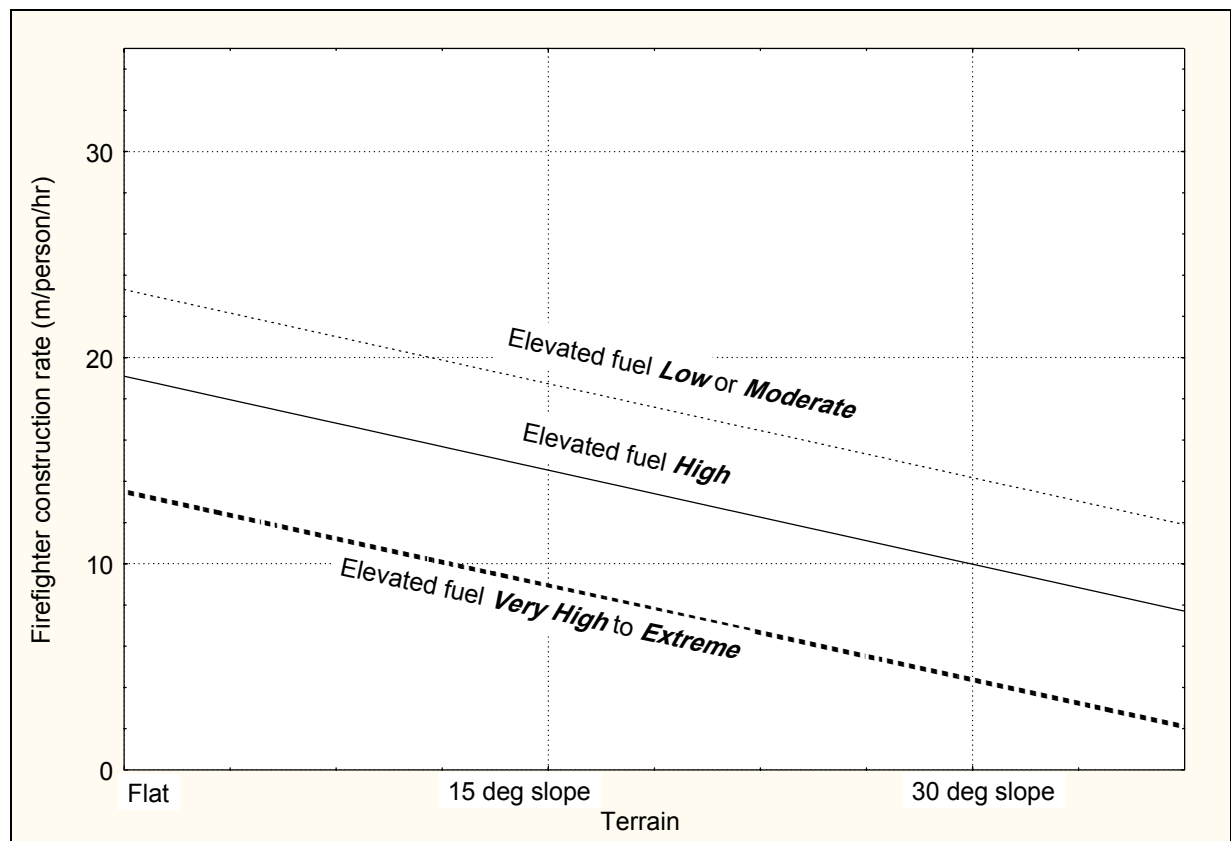
Note: elevated fuel restriction is expressed in terms of the elevated fuel hazard assessment system outlined in the Overall Fuel Hazard Guide (McCarthy et al. 1999).

Figure 2 and Equation 1 were able to explain approximately 49% of the variation in the data.

The next most important factor affecting the construction rates of hand trails was the presence of active fire on the fireline under construction. Active fire in this situation was considered to be flame 0.3 m or higher within 5 metres of the hand trail - this was taken to be the lowest threshold at which radiant heat and smoke would inhibit crew activities doing line construction. A three-factor linear model, using the presence of active fire along the line being constructed was able to explain a further 8% of variation in the data

This model is described by Equation 2:

FFrate = 27 + ((-10.3)*FFterr) + ((-16.2)*FFelev) + (-6.8*Actvsupp)   **Equation 2**

$$(n=29, r^2=0.57, p<001)$$

Where:

   FFrate = Firefighter rate of line construction

   FFterr = restriction on firefighters due to the presence of adverse terrain, mostly slope[3]

   FFelev = restriction on firefighters due to the presence of elevated fuel

   Actvsupp = presence of active fire on the fireline being constructed

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A summary of the contribution each of the three factors makes toward explaining the variation in the data is:

Variable	Proportion of variation in data explained
Restriction on firefighters due to the presence of adverse terrain, mostly slope[3]	29%
Restriction on firefighters due to the presence of elevated fuel	19%
Presence of active fire on the fireline being constructed	8%

The difference in fitness levels between an ordinary crew, who were rated by most fire managers at a fitness level of between 75% and 80%, and rappel crews—rated at 90–95% fitness, could explain another 5% of the variation in the data. However, this trend was only apparent when some of the outlier data points were removed from the data set and, as a result, was not specifically used in the analysis.

Note 3:   It is notable that the limitation imposed by slope at the fireline (from measurements at the site and/or topographic data) did not correlate as well with construction rates as did all terrain-associated factors. As a result, the 'Ffterr' variable shown in the above models expresses more than just 'slope'. Rather, it expresses the fireline supervisors' opinions of the difficulty of the terrain in terms of slope variations, position in the landscape and ground conditions, as well as slope angle. The difficulty of expressing this in a predictive way for the purposes of modelling meant that it had to be expressed as merely a slope class. Fire managers should keep this in mind when using the models. An example of how this terrain limitation variable may vary would be to compare the situation of a fire in steep terrain on an Alpine Ash (*Eucalyptus delegatensis*) site—mid-slope on a dissected, high mountain range with loose soil and rock underfoot, with that of a fire on a steeper slope in low foothill country—with little slope variation, less slope length in the landscape and compacted soil with few rocks. In future work, it would be wise to attempt to better differentiate this terrain limitation factor during data collection.

Uphill or downhill did not make much difference to the amount of line constructed except that, as handtrail construction is rarely attempted on steep uphill slopes, this sort of construction is not included in the data. Data on construction downhill on steep slopes are included, but increasing steepness downhill tended to reduce construction rates slightly, as crews found it more difficult to maintain their footing.

D4 bulldozer line construction rates

Figure 3 shows D4 bulldozer line construction rates modelled as a function of the effect of adverse terrain and debris. It indicates that the effect of terrain and debris can explain almost 50% of the variation in the data. This was the best two-factor linear model to predict D4 fireline construction rates.

The equation describing the model in Figure 3 is:

D4rate = 673 + ((-635)*DozTerr) + ((-413)*Dozdebris)   **Equation 3**

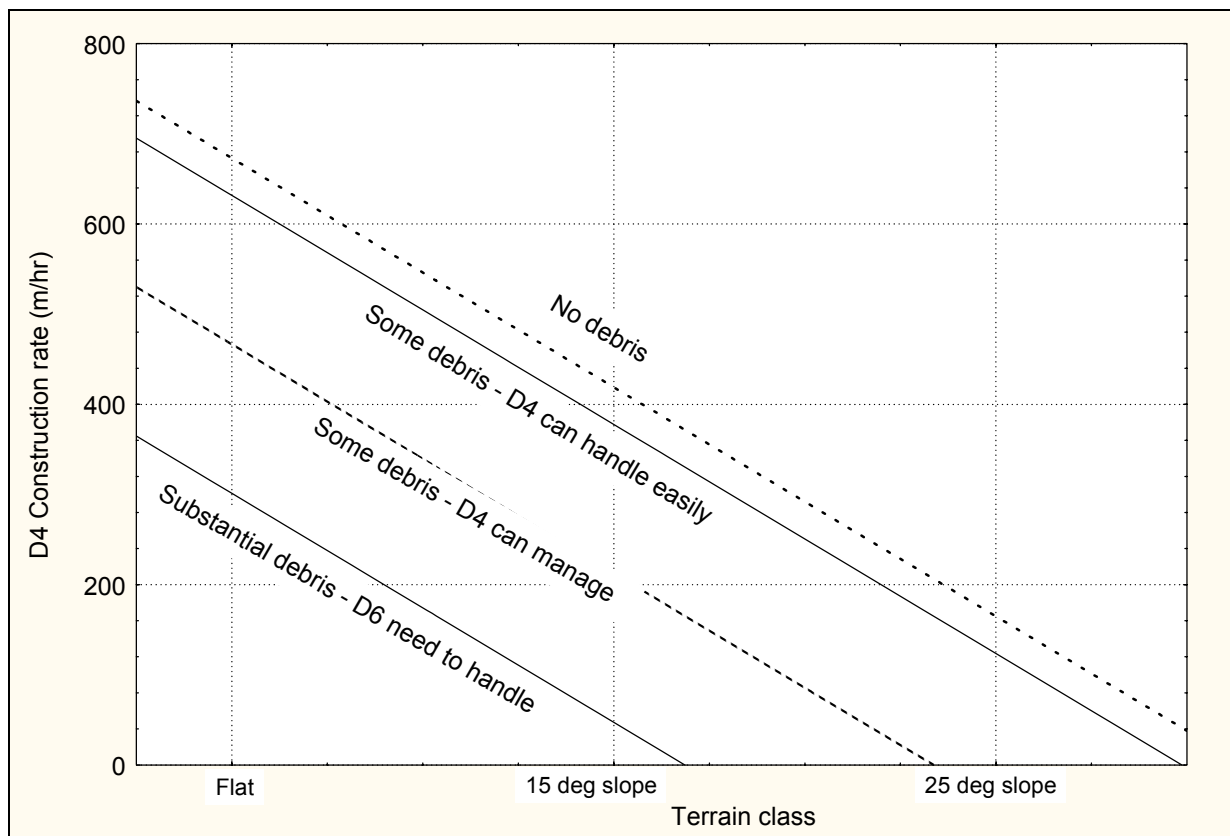$$(n=29,\ r^2=0.47,\ p<001)$$

Where:

      D4rate = D4 rate of line construction

      Dozterr = restriction on dozer due to the presence of adverse terrain, mostly slope[4]

      Dozdebris = restriction on dozer due to the presence of debris: standing dead and live material, old logs elevated fuel

---

Figure 3   Model for D4 bulldozer construction rates based on effect of adverse terrain and debris

The left-hand end of the plot indicates a slight increase in construction rates when working downhill. In reality, this increase is only likely to apply in situations where D4 bulldozers can construct trail on relatively gentle down-slopes and in the absence of much debris—substantial debris would force the machine to constantly back up. Accordingly, the increase in construction rate shown for down-slopes where substantial debris occurs is an artefact of the model and will not reflect reality.

The next most important factor affecting D4 construction rates was the experience of the operator in terrain and vegetation similar to the fire site.

A three-factor non-linear model, using operator experience (in terrain and vegetation similar to the fire's site) was able to explain another 28% of variation in the data.

Equation 4 describes this model:

D4rate = 595 + ((651)*Dozterr) + ((-234)*Dozdebris) + (1/exp (-0.19* Opterr)   Equation 4

$$(n = 29, r^2 = 0.79, p<0.001)$$

Where:

   D4rate = D4 rate of line construction

   Dozterr = restriction on dozer due to the presence of adverse terrain, mostly slope[4]

   Dozdebris = restriction on dozer due to the presence of debris: standing dead and live material, old logs elevated fuel

   Opterr = experience in years of the operator in terrain and vegetation similar to the fire site

A summary of the contribution each of the three factors makes toward explaining the variation in the data is:

Variable	Proportion of variation in data explained
Restriction on bulldozer due to the presence of adverse terrain, mostly slope[4]	29%
Restriction on bulldozer due to the presence of debris: standing dead and live material, old logs, elevated fuel	19%
Operator experience in years, in terrain and vegetation similar to the fire site	28%

Note 4:   It is notable that the limitation imposed by slope at the fireline (from measurements at the site and/or topographic data) did not correlate as well with construction rates as did all terrain-associated factors. As a result, the 'Dozterr' variable shown in the above models expresses more than just 'slope'. Rather, it expresses the fireline supervisors' opinions of the difficulty of the terrain in terms of slope variations, terrain dissection, position in the landscape and ground conditions, as well as slope angle. The difficulty of expressing this in a predictive way for the purposes of modelling meant that it had to be expressed as merely a slope class. Fire managers should keep this in mind when using the models. In future work, it would be wise to attempt to better differentiate this terrain limitation factor during data collection.

Uphill or downhill construction did not make much difference to the amount of line constructed. It should be noted that machine construction of firelines is rarely attempted on steep uphills, and therefore rates for this sort of construction are not included in the data. Some downhill construction by machines was somewhat faster on shallower slopes—although this again depended more on the amount of debris encountered. The 'Dozterr' variable also expresses the increased rates of fireline construction sometimes experienced on downhill slopes.

D6 bulldozer line construction rates

Figure 4 shows D6 bulldozer line construction rates modelled as a function of the effect of debris and limitation due to rock. It shows that both debris and rock can significantly affect construction rates. This model was able to explain nearly 65% of the variation in the data.

Equation 5 explains this model:

D6rate = 951 + (-728*Dozdebris) + (-750*Dozrock)   Equation 5

$$(n = 16, r^2 = 0.64, p<0.001)$$

Where:

   D6rate = D6 rate of line construction

    Dozrock = restriction on dozer due to the presence of rock (both surface and subsurface)

    Dozdebris = restriction on dozer due to the presence of debris: standing dead and live material, old logs, thicker elevated fuel

Figure 4   Model for D6 bulldozer construction rates based on effect of debris and limitation due to the presence of rock
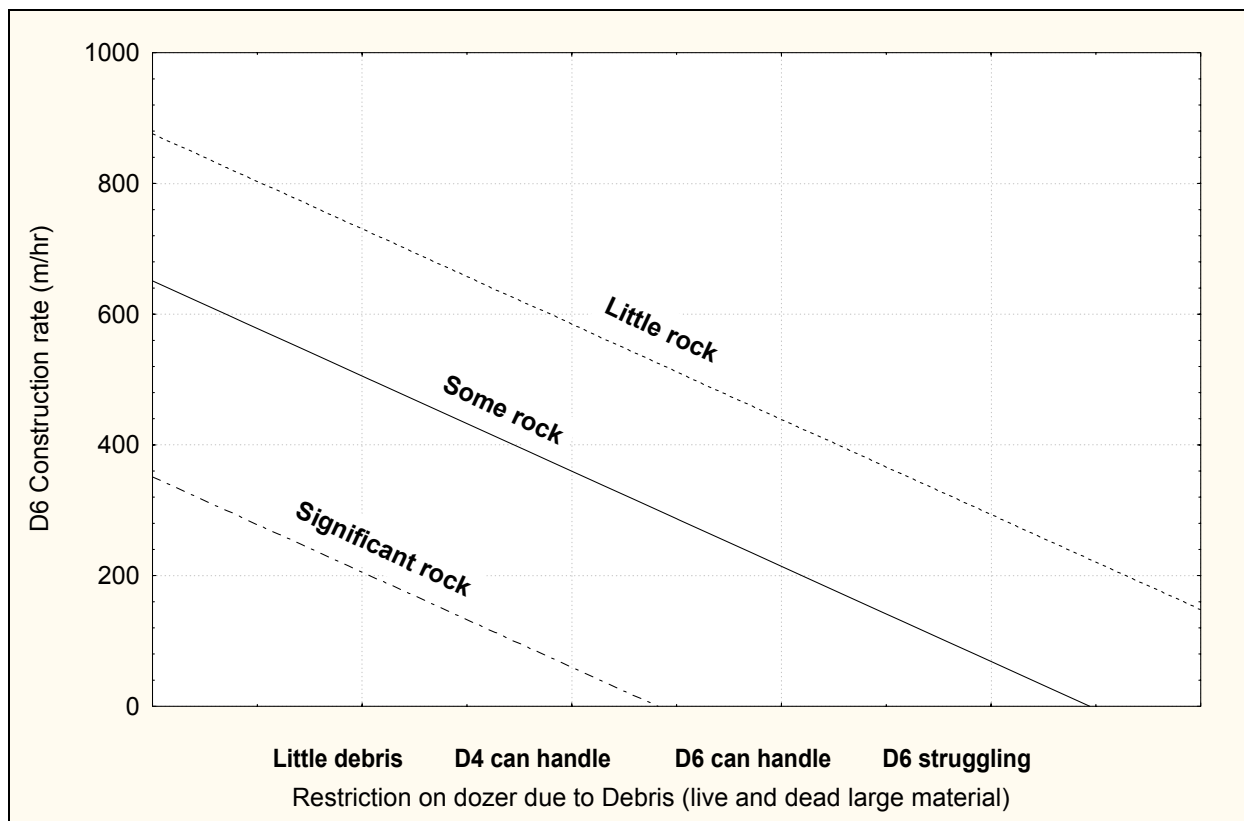
The next most important factor affecting D6 construction rates was operator experience, with construction rates reducing by a further 10–20% for an inexperienced operator.

A three-factor linear model, described by Equation 6 (in which overall operator experience is combined with debris and rock) was able to explain a further 22% in the variation in the data (i.e. r^2=0.86). Note that this model is derived from only eight observations and will therefore not be very robust.

D6rate = 881 + ((-813)*Dozdebris) + ((-765)*Dozrock) + (11.1* Opexyrs)   Equation 6

$$ (n = 8, r^2 = 0.86, p<0.01) $$

Where:

    D6rate = D6 rate of line construction

    Dozrock = restriction on dozer due to the presence of rock (both surface and subsurface)

    Dozdebris = restriction on dozer due to the presence of debris: standing dead and live material, old logs, thicker elevated fuel

    Opexyrs = overall experience in years of the operator

A summary of the contribution each of the three factors makes toward explaining the variation in the data is:

Variable	Proportion of variation in data explained
Restriction on bulldozer due to the presence of debris: standing dead and live material, old logs, elevated fuel	37%
Restriction on bulldozer due to the presence of rock, both surface and subsurface	27%
Operator experience overall (in years)	22%

Large bulldozer line construction rates

Figure 5 shows large bulldozer line construction rates modelled as a function of the effect of debris and limitation due to terrain. It shows, in contrast to the model for D6 bulldozers, that the effects of debris and slope were most important in explaining the variation in construction rates. This model was able to explain approximately 58% of the variation in the data.

Equation 7 explains this model:

D6+rate = 956 + (-16*Slope) + (-601*Dozdebris)   Equation 7

$$(n = 35, r^2 = 0.58, p<0.001)$$

Where:

    D6+rate = D6+ rate of line construction

    Slope = average slope for that section of fireline (in degrees)

    Dozdebris = restriction on dozer due to the presence of debris: standing dead and live material, old logs, thicker elevated fuel

Figure 5   Model for large bulldozer (D6–D9) construction rates based on effect of debris and limitation due to the presence of adverse terrain

Similar to the models for D6 construction rates, operator experience was the third most important factor in explaining variations in the data.

A three-factor linear model, described by Equation 8 (in which overall operator experience is combined with slope and debris), was able to explain a further 12% in the variation in the data (i.e. r^2=0.70).

D6+rate = 942 + (-703*Dozdebris) + (-16*Slope) + (6* Opexyrs)   Equation 8
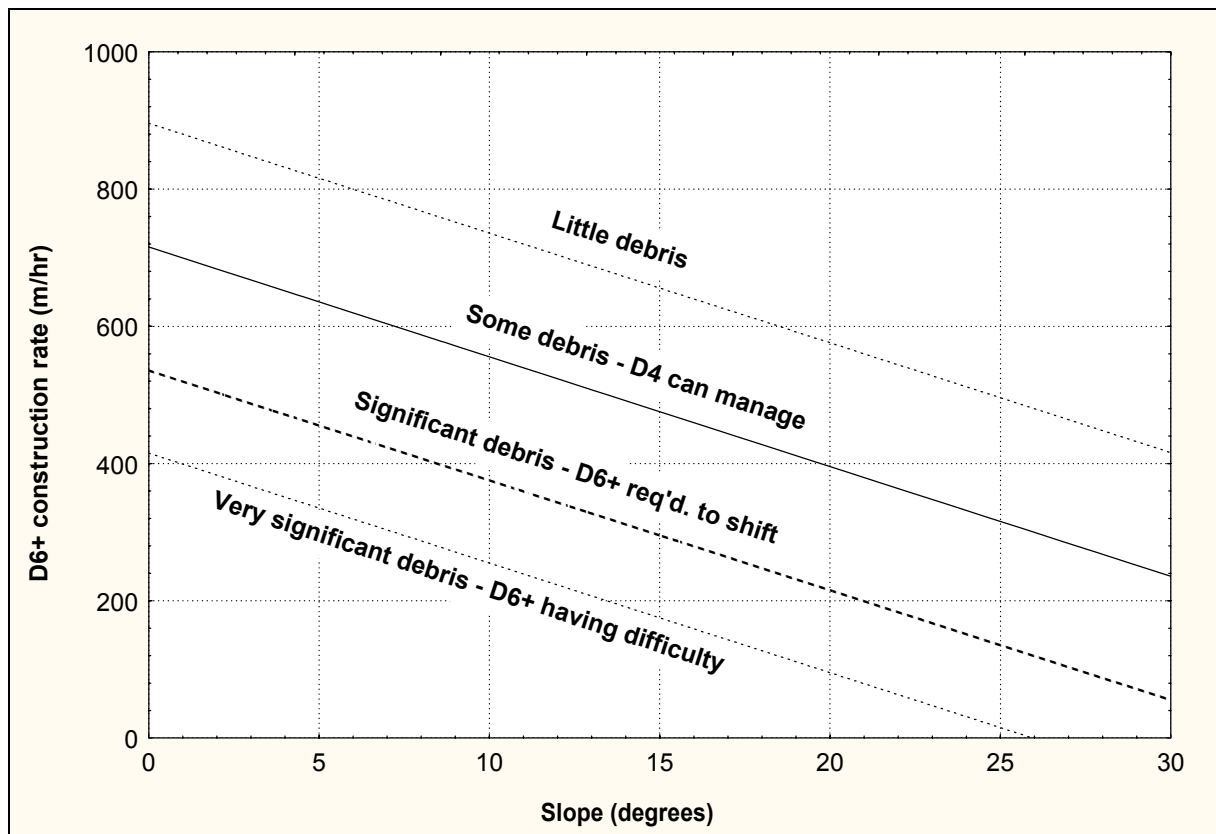
$$(n = 24, r^2 = 0.70, p<0.01)$$

Where:

    D6+rate = D6+ rate of line construction

    Slope = average slope of that section of fireline (in degrees)

    Dozdebris = restriction on dozer due to the presence of debris: standing dead and live material, old logs, thicker elevated fuel

    Opexyrs = overall experience in years of the operator

A summary of the contribution each of the three factors makes toward explaining the variation in the data is:

Variable	Proportion of variation in data explained
Restriction on bulldozer due to the presence of debris: standing dead and live material, old logs, elevated fuel	27%
Restriction on bulldozer due to slope (average slope for section of fireline)	21%
Operator experience overall in years	12%

Limitations due to rock were still important. A four-factor model which included limitations due to rock was able to explain a further 4% of variation in the data.

Resource combinations

Table 4 is based on relatively loose trends in the data. It has not been derived from any valid statistical analyses, but rather has been constructed by general comparisons of fireline length with the level of various resources involved. It is presented to indicate the minimum level of resources that were required to contain a given length of fireline.

Table 4   Resource combinations associated with various fireline lengths

Fireline length	Resource combination
<1000 m	4–6 firefighters, 1–2 slip-ons, 1 D4 bulldozer (for bulldozer-accessible fires)
	10–20 firefighters for hand-trail only fires
1000–2000 m	10–15 firefighters, 3–6 slip-ons, 1 large tanker, 1 D4 and/or D6 bulldozer (for bulldozer-accessible fires)
	15–25 firefighters for hand-trail only fires
2000+ m	20–50 firefighters for hand-trail only fires (up to 3000–4000 m total fireline length, and supported by aircraft)
	D6+ bulldozers - numbers according to length of fireline and an average rate of construction of 700–800 m/hr (vary for rock and terrain according to the models above)

Resource deficiencies and excesses

Table 1 indicates that, when fire managers were asked to nominate which resources they could have used (hypothetically) in addition to those actually available, the most common response was that the resources allocated were adequate for the suppression task in hand.

In the few instances where fire managers nominated desirable extra resources (that is, hypothetical additional resources which they considered would have increased the effectiveness of the suppression operation), they nominated:

- extra firefighters, particularly for construction of hand trails
- extra tankers (mostly slip-ons but occasionally large tankers), particularly where more knockdown and wetting capability would have been useful
- extra D6-size bulldozers where bulldozer line construction was the main task
- extra medium helicopters, particularly where wetting the fireline, knockdown and support of ground forces was important.

The arrival of resources surplus to those required to achieve effective fire suppression was also, in the opinion of most fire managers, a fairly infrequent occurrence. Some Departmental fire managers in Victoria's west said that, on occasions, and generally because of the nature of the public/private land matrix in the area, more Country Fire Authority (CFA) large tankers than could be effectively utilised arrived at Departmental forest fires. (Conversely, the CFA sometimes provides effective 'first attack' on some of these fires on public land.)

Discussion

The most important finding of this study is that fireline construction rates obtained under real fire conditions can often be substantially less than those achieved under experimental conditions. This is particularly the case for the rates of construction of hand trails.

A second important finding, similar to results from studies elsewhere, is that fireline construction rates are *very variable* and often depend on factors (in addition to those listed below) that are beyond the control of the construction crews and machines. Examples of these, from anecdotal information collected during this study, include equipment malfunctions, problems during shift changeover, absence of aircraft support in indicating direction to a fire and lack of local knowledge.

Hand trail construction

The rates for construction of hand trails under actual fire-suppression conditions recorded in this study are substantially less than rates obtained under experimental conditions. The main factors responsible for the variation in the observed rates were:

- the presence of elevated fuels - which substantially reduced construction rates
- the presence of adverse terrain - which also substantially reduced construction rates
- the proximity of the fire to the fireline - higher flames close to the fireline caused crews to both slow down and retreat to a safer distance from the active fire front.

Another factor apparently influencing construction rates (when some of the outlier data points were removed to form a restricted data set) was the fitness levels of the crews. The fittest crews, particularly those, such as rappel crews, who did daily aerobic exercise, were in some situations able to construct more fireline per person in the same time as normal crews. This finding concurs with those of Project Aquarius (Budd et al. 1996), where fitness levels were also found to influence hand trail construction.

Studies into construction rates of hand trail firelines conducted in USA were summarised in Haven et al. (1982). These authors report very large variations in construction rates, depending on the specific study and the number of observations. They noted that the studies with the greater number of observations reported generally lower construction rates. They separated various groups of rates by "fuel resistance-to-control classes". Although comparisons between USA conditions and those found in Australia are tenuous at best, it is worth noting that hand trail construction rates in forest situations in USA ranged from about 25 m/person/hr down to about 5 m/person/hr. The lower rates were almost certainly associated with firelines dug into deep humus layers in mountain forests (as reported by many members of the Australian firefighting contingent sent to USA in 2000 to assist with fires in the Northern Rocky Mountains - J. McI. McDonald pers. comm.).

A later USA study (Barney et al. 1992) found that crew size appeared to be one of the main determinants of hand trail construction rates. Importantly they found that 'Hotshot' and 'Smokejumper' crews were able to produce slightly more fireline than normal crews over the same time period. This concurs with the findings of this study where rappel crews were slightly more productive than ordinary crews.

These authors also found that various factors started to operate when crew numbers exceeded 20[5] persons such that construction rates started to flatten off. They also differentiated construction rates by broad vegetation type and soil type, with construction rates being slower in mixed hardwood and softwood stands and slower in rocky soils.

A fireline construction demonstration held in north-east Victoria in the 1980s (DCE 1991) indicated that a six-person hand-trail crew could achieve rates of 210 m/person/hr. Crichton and Dawson (1986), reporting on the achievements of hand trail crews tested in association with Project Aquarius (WA and Vic), outline upper and lower limits of productivity of approximately 240 m/person/hr down to 70 m/person/hr; the mean total figures for each length of line raked being approximately 70 m/person/hr.

Figures from the Western Australia Forest Fire Behaviour Tables (Sneeuwjagt & Peet 1985) suggest that, in lighter fuels (Northern Jarrah), five-person crews should achieve between 65 m/person/hr and 35 m/person/hr depending on the Fire Danger Index (FDI) on the day. For heavier fuels (Southern Jarrah), they suggest that these rates will range from 40 m/person/hr down to 15 m/person/hr, again depending on the FDI on the day.

The WA figures can be compared to the two highest rates of actual fireline productivity (35 m/person/hr and 44 m/person/hr) from the present study. The 35 m/person/hr was achieved by a rappel crew in relatively even terrain with little elevated fuel. This crew had high levels of aerobic fitness and good firefighting experience working as a team; a number of the members had been in the same crew for the previous 3–5 fire seasons. The rate of 44 m/person/hr was achieved by a combination of rappel crew and relatively fit summer crew working downhill in very light elevated fuels and where the surface fuels was disturbed by animal tracks and soil erosion. This crew was also trying to beat a fire on the slope opposite them to the bottom of a gully and were working in quite mild weather conditions in Autumn.

Actual productivity figures tended to drop significantly where slightly less fit crews were used and steeper terrain and thick elevated fuels were encountered. Construction rates of between 5 and 10 m/person/hour were recorded in this study for a number of fire situations in mountainous terrain in Alpine Ash (*Eucalyptus delegatensis*) and high elevation mixed eucalypt species (HEMS) vegetation types. This concurred well with the figures reported by Caddell (1994) who recorded actual fireline construction rates for a number of fires in steep terrain in north-east Victoria in the 1980s.

This strongly indicates that adopting construction rates obtained under demonstration conditions for planning purposes will significantly over-estimate likely achievements.

The rates obtained from demonstrations or experiments seem to neglect the need for the crew to actually achieve control of the fire. It is likely that additional tasks involved in actual operations - such as patrol, communications and supervision - add significantly to the overall time required for 'real' fireline construction.

It is also likely that real crews tend to set a rate of construction which they can maintain for a much longer period of time, especially as the length of line to be constructed and the time to be spent constructing it is not always well known in advance.

Note 5:   This may help to explain why some large crews at the Caledonia fire were reportedly producing only as much fireline per person as some smaller crews in similar circumstances - K.G. Tolhurst pers. comm.

Bulldozer fireline construction

The findings of this study generally concur with those from the few available similar studies in Australia and overseas. That is, that the major influences on bulldozer fireline construction rates are:

- size of the machine - larger bulldozers are generally faster than smaller ones

- the terrain in which the fireline is being constructed—fireline construction rates generally reduce on steeper slopes; although the rate may actually increase on some down-slopes

- the vegetation type in which the line is being constructed - increased live vegetation and dead/down debris reduces construction rates

- the experience of the operator - experienced operators, particularly with experience in more difficult terrain and vegetation, are substantially faster at constructing fireline than inexperienced operators

- the amount of rock occurring along the fireline - rocks can both slow construction and significantly reduce the ability of the bulldozer to back up in tight situations.

The models determined from this study for all types of bulldozers also show construction rates that are a little lower than those obtained from experiments and demonstrations. This was particularly the case for some of the D7- and D9-sized bulldozers, and particularly where these machines were not 'forest' machines—that is, they were road-construction machines hired at short notice for firefighting. This indicates that construction rates obtained from experiments or demonstrations may overestimate those likely to be obtained under actual fireline conditions, especially when bulldozers are not ideal and operators are not familiar with firefighting conditions.

The Basic Fire Control Manual (DCE 1991) includes rates obtained from tests in the USA in 1948 (Arcadia Equipment Development Centre, US Forest Service, Report No. 13). The Manual states that these rates were obtained under ideal ground conditions (no rocks and no logs). Updated USA data (Phillips et al. 1988) are difficult to interpret as they contain many combinations of fire behaviour fuel models (FBFMs), variations of up-slopes and down-slopes and three different sizes of bulldozer. While the maximum construction rates from USA studies are generally similar to those obtained in this study (Figures 3, 4 & 5 above), the rates for steeper terrain and heavier scrub are somewhat greater. For example, the rate in the 1948 USA tables of 260 m/hr for a D4 in steeper terrain and heavy scrub (and about 300 m/hr from the 1988 USA models, which used a number of assumptions for the fuel and slope classes), compares well with a prediction of 200 m/hr or less for the model given in Figure 3.

To compare any Australian situation with the models in Phillips et al. 1988 would be questionable. Dissimilarities in fuel, terrain and task conditions are such that these tables may not be of much use to Australian fire managers. The USA studies nevertheless confirm many of the difficulties faced in collecting data on fireline construction rates and many of the factors which contributed to the large variation in the rates observed. The authors noted that:

- reliable information on actual construction rates under wildfire conditions was very difficult to obtain

- variation in construction rates was large and influenced by many factors

- fuel conditions (FBFMs) affected line construction rates significantly

- large amounts of rock was a significant impediment to line construction

- there were significant differences between up-slope and down-slope construction rates

- machine age and operator experience were significant contributing factors.

What is also useful from the most recent USA study (Phillips et al. 1988) is the way their models for bulldozer fireline are constructed. They use bulldozer size, slope class and vegetation type as the main predictors of likely line construction rates. This is quite similar to the important independent variables used to derive the models in Figures 3, 4 and 5 in the present study.

Fried and Gilless (1989) applied the significantly different approach of seeking expert opinion on a range of hypothetical fireline sites (in western USA) to derive estimated fireline construction times by various methods. The similarities in the results obtained from individual firefighting experts (interviewed independently) were so good that the authors concluded that this method was valid for deriving likely fireline construction rates. As was also found in the present study, they noted that the rates predicted from experiments were sometimes wildly optimistic and that fireline construction rates actually achieved were often hampered by factors that did not occur under experimental conditions.

A method which Fried and Gilless (1989) used, which may have merit for future work in this field, was to ask the firefighting experts for three estimates of time to construct a given length of line, these being:

- an estimate of the shortest possible time in which the line may be completed - i.e. the day where everything went smoothly with no breakdowns or delays (T_{min})

- an estimate of the most likely time for the line to be completed - i.e. the day which had the 'normal' number of obstructions and delays (T_{mode})

- an estimate of the worst possible time for the line to be constructed - i.e. the day when everything went wrong, and the greatest degree of difficulty was experienced in achieving line completion. (T_{max})

From these time estimates they were able to construct a time distribution curve which was then used to derive a mean time for construction, and hence a mean construction rate. The rates obtained by this methodology appeared to be closer to those obtained in the present study, although again, differences in fuels, terrain and construction tasks may make comparisons with local data highly suspect.

The lower mean rates shown in Table 2 for D7s and D9s, compared to D6s, are likely to be a function of the small data sets for the larger machines. It is unlikely that this size of machine would be appreciably slower than a D6 with similar operators and operating conditions. However, there may be, even for this small sample, an effect arising from the likelihood that these larger machines were earthmoving machines which do not spend much time in forested country and are more likely to be driven by operators who do not have much experience working in forested terrain. Many D6s, on the other hand, are logging machines which spend the majority of their operating life in forested environments. The average figures for experience (in terrain and vegetation similar to the fire site) of 8.6 years for D7/D9 operators, compared to 11.5 years for D6 operators, supports this.

Specialised machinery

In some cases, fire districts use specialised machinery for construction of firelines in fuel types specific to that district.

Shepparton Fire District, for instance, sometimes uses a Bobcat—a small rubber-tyred tractor with a front-mounted combination bucket and blade—for fires in red gum forests. This machine is carried rapidly to the fire area on either a long trailer or a tipper truck. It is small enough to fit readily between trees, even regrowth, and can move around much of the fallen debris found in these forests. It can rapidly scrape off any grass cover and work very close to the fireline. It is relatively fast at line construction, being able to construct between 500 and 1200 m/hr depending on the fuel and fire behaviour.

Mildura Fire District uses a contract D3 bulldozer fitted with a hydraulic angle and tilt blade and transported on a dedicated tipper truck. This machine is small enough to fit between most of the mallee-sized trees in the local fuel complexes, performing almost like a large mobile rakehoe. Although the fireline it constructs is only about 1.5 m wide, this is often quite adequate in these lighter fuels

Horsham and Portland Fire Districts use a number of wheeled tractors, depending on the fuel complex. They can move through quite tall scrub (like some desert fuels) and push a reasonable amount of material if it is fairly light, but are restricted by heavier forest fuels and become ineffective with closer-standing trees and heavy debris such as fallen logs.

Large wheeled tractors with rear-mounted slashers have been used in firefighting in coastal heathlands (McCarthy & Tolhurst 1995) and enable the construction of useful firebreaks in these fuels types with minimal disturbance to the soil surface.

Tanker fireline holding rates

The wide variation in the data for fireline holding rates using tankers indicates that this suppression method is highly dependent on both fire behaviour and the ease of access for the tanker to the fire front. That is, if tankers are able to get in close to the fireline, the flame depth is not great and there is little restriction to vehicular access, relatively large holding rates can be achieved. The maximum recorded holding rate in the current study was 800 m/hr; higher rates are likely to be achieved in light grassy fuels in flat terrain. The lowest holding rate recorded of only 100 m/hr was associated with rates of spread of the fire of 500 m/hr (or more), flame heights of 1.5–2.0 m and spotting distances of 50–75 m. Fire behaviour in this case prevented rapid knockdown by water, forcing the tanker crews to work quite hard to knock down a relatively small distance of fireline over an extended period.

The most significant factors explaining the variation in tanker holding rates are wind speed and fuel hazard. The lowest holding rate mentioned above was associated with high wind speeds (25–30 km/hr) and a bark hazard of *Very High* to *Extreme* which contributed directly to both the fire behaviour and the difficulty of suppression.

Research in USA by Fried and Gilless (1989), using expert opinion, suggested a tanker knockdown range of between 600 m/hr and 2000 m/hr depending on the fuel type and slope class. That study only looked at mobile tanker knockdown rates in grass and sagebrush and did not sample forest fuel types. They did report on hose-lay knockdown in forest, with rates of between 200 m/hr and 400 m/hr, again depending on slope.

Firebomber fireline holding rates

The relatively small amount of data on firebomber line holding rates is a little less variable than that for tankers. The variation between 80 m/hr and 300 m/hr is best explained by variations in both wind speed and the amount of live and dead debris at the fire site. Stronger winds make the task of laying retardant by aircraft much more hazardous and less effective. The amount of live and dead debris on the ground also increases the difficulty for firebombers to achieve consistently well-held fireline; this was reported by McCarthy and Tolhurst (1995) for fire in the Wilsons Promontory National Park.

Firebomber line holding rates will also be greatly influenced by both the drop pattern of the aircraft (Rees 1983) and their turnaround times (McCarthy 2003). Theoretical line holding rates could be calculated for most firebombing operations using these two main variables which could then be adjusted downward according to the amount of wind and the thickness of the vegetation on the site.

Contribution of aircraft resources

An important finding of the present study was that aircraft were either crucial or highly important to the containment effort at about 40% of the fire events. Although aircraft resources are not always available due to distance, atmospheric conditions, other fire events and daylight restrictions, it appears that, where they are used, they are able to make an important contribution to early containment of many fire events.

Many fire managers commented that, without the assistance of aircraft on the first day, the fire would have progressed into the next day shift and often longer. That is, they observed that aircraft helped significantly in slowing (and sometimes stopping) the head fire sufficiently to enable ground crews to complete a containment fireline either that day or during the first night. This is consistent with the findings of McCarthy (2003) in regard to the usefulness of firefighting aircraft in Victoria.

Although a very variable and highly subjective assessment, when fire managers were asked to estimate how much time the work by the aircraft may have saved in the context of the overall time taken for containment of a fire, a mean figure of 4.5 hours was obtained. This mean figure derives from the 49 fires at which aircraft were prominent in the suppression effort. Despite the imprecision of this estimate, it nevertheless highlights that, as a firefighting resource, aircraft can be quite significant in reducing the length of the final containment line and thereby reduce the overall task for the ground forces.

Resource combinations

Whilst this study did not look in detail at the effectiveness of specific combinations of resources, those in Table 4 are based on observations from successfully contained fires. They could therefore be used as a guide to fire managers in setting minimum resource levels for firelines of the lengths nominated and provide a safeguard against possible under-resourcing.

While some data on resource combinations were collected during the present study, they were not sufficient to analyse trends or make specific conclusions. Accordingly, the effectiveness of various resource combinations, particularly to highlight those combinations critical for successful containment, is worthy of further study.

Requirement for extra (hypothetical) resources

Fire managers were asked to nominate hypothetical extra resources which, had they been available, would have increased the effectiveness of the suppression operation. The most important ones nominated were:

- more firefighters, particularly for fires where longer hand trails were involved
- more tankers (both large and slip-ons), particularly to assist with patrol of longer lengths of fresh bulldozer trail
- extra D6-size bulldozers where bulldozer line construction was the main task
- more tactical aircraft, particularly medium helicopters and fixed-wing firebombers, especially at fires where it was difficult for ground crews to directly attack the headfire.

The mean figures expressing the requirement for extra resources are significant by their small size. This suggests that overall resourcing was generally adequate for the containment tasks at hand and that the occasions on which extra resources were required were the exceptions rather than the normal case.

This does not mean that the level of resourcing is always adequate, however. In the few instances where first attack, or extended first attack, fails (McCarthy & Tolhurst 1998), there will always be a problem of under-resourcing while the fire is rapidly increasing in perimeter. Nevertheless, during this rapid and intense period of fire growth there are few resources that

will be effective near the head fire. Rather, it will be a challenge for fire managers to adequately resource the fireline construction task once the fire has grown to near its final size.

The Aircrane heavy helicopter was one new item of equipment which some fire managers nominated as a desirable hypothetical extra resource. The Aircrane, with its 9000-litre capacity and high manoeuvrability, was considered to have been a highly useful addition to existing forces had it been available. This was particularly the case where asset protection was of high importance.

Resources in excess of those required

The low mean figures for resources in excess to those required also suggest that over-resourcing is an exception rather than a regular occurrence. Almost the only over-resourcing events recorded were the arrival of excess numbers of Country Fire Authority (CFA) large tanker units at Departmental-controlled fires in some locations in Western Victoria. This was generally not considered a problem, however, and many fire managers said that they would prefer a significant CFA response to a weak or non-existent one. They also commented that it was relatively easy to either stand down, or re-allocate, these resources if required.

Conclusions

Hand trail construction rates achieved at actual fires are significantly lower than those achieved under experimental or demonstration conditions.

Bulldozer construction rates are significantly influenced by debris (both live and dead), rock and terrain and, to a lesser extent, the experience of the operator. Bulldozer construction rates may also be somewhat less than those suggested from experiments or demonstrations.

Tactical aircraft, if present, can significantly assist with fire containment and often reduce the amount of fireline which must eventually be constructed by ground forces

The effectiveness of various combinations of firefighting resources is important and requires further study. Fireline perimeter (current or predicted) can give some indication of the likely combination of resources required for containment.

Under- or over-resourcing at fires is not common.

References

Barney, RJ, George, CW & Trethewey, DL 1992, Handcrew fireline production rates. USDA Forest Service, Intermountain Research Station, Research Paper, INT-457.

Budd, GM, Brotherhood, JR, Hendrie, AL, Cheney, NP & Dawson, MP 1996, Safe and productive bushfire fighting with handtools. Australian Government Publishing Service.

Caddell, R 1994, 'Fireline construction notes', presentation notes prepared for Operations Officer Level 3 course. Department of Conservation and Natural Resources, (Vic. Aust.).

Crichton, TP & Dawson, MP 1986, 'Fire suppression studies of ground crews during Project Aquarius', progress report to Country Fire Services, South Australia.

DCE 1991, 'Basic Fire Control Manual 1991 Edition' (unpubl.), Fire Management Branch, Department of Conservation and Environment (Vic. Aust.)

Fried, JS & Gilless, JK 1989, Expert opinion estimation of fireline production rates. *Forest Science* 35(3); pp 870–877.

McCarthy, GJ 2003, Effectiveness of aircraft operations by the Department of Natural Resources and Environment and the Country Fire Authority 1997–98. *Research Report* No. 52. Fire Management, Department of Sustainability and Environment (Vic. Aust.).

McCarthy, GJ & Tolhurst, KG 1995, 'An analysis of the suppression options at Chinaman Long Beach fire - Yarram Fire Y016, Wilsons Promontory National Park, 12 & 13 February 1995', internal report to Chief Fire Officer, Fire Management Branch, Department of Conservation and Natural Resources (Vic. Aust.).

McCarthy, GJ & Tolhurst, KG 1998, Effectiveness of fire-fighting first attack operations, DNRE Victoria 1991/92-1994/95. *Research Report* No. 45. Fire Management Branch. Department of Natural Resources and Environment (Vic. Aust.).

McCarthy, G J, Tolhurst, KG & Chatto, C 1999, Overall fuel hazard guide (3rd Edition), *Research Report* No. 47. Fire Management. Department of Natural Resources and Environment (Vic. Aust.).

Phillips, BP, George, CW & Nelson, DK 1988, Bulldozer fireline production rates - 1988 Update. USDA Forests Service Intermountain Research Station, Research Paper INT-392, June 1988.

Haven, L, Hunter, TP & Storey, TG 1982, Production rates for crews using hand tools on firelines. USDA Forests Service Pacific Southwest Forest and Range Experiment Station, General Technical Report PSW-62

Rees, B 1983, Retardant distributions from six agricultural aircraft. *Research Report* No. 18. Fire Protection Branch, Department of Conservation, Forests and Lands (Vic., Aust.).

Sneeuwjagt, RJ & Peet, GB 1985, Forest fire behaviour tables for Western Australia (3rd Edition). Department of Conservation and Land Management (WA, Aust.).

Appendix

Park and forest firefighting resources guide

Park and forest firefighting resources guide

December 2003

Fire Management

Victoria
The Place To Be

Contents

Introduction

This guide aims to assist Victorian park and forest fire managers in making decisions about the level of firefighting resources required to construct firelines under a range of topographic, and vegetation or debris conditions.

Because of the high variability of conditions found in Victoria's parks and forests, this guide should not be treated as a definitive statement of the level of resources required. It is intended more to indicate the approximate levels required and to avoid situations where resource requirements are excessively under or over estimated.

The data supporting this guide were derived from observations made during over 100 fire-control operations. To further improve this guide, the opportunistic collection of information about construction rates of fire-control lines, or holding rates by tankers or firebombers, and associated environmental and resourcing data, would be appreciated and should be directed to the Department's Fire Management.

Gary Morgan
Chief Fire Officer

About this guide

This guide is based on the Fire Management Research Report 'Prediction of Firefighting Resources for Suppression Operations in Victoria's Parks and Forests' (2003).

Fireline construction rates vary widely with environmental conditions, equipment and fitness of firefighters. Consequently, the models set out in this guide should only be used to give an approximate prediction of likely rates. They are presented principally to assist fire managers in estimating required resource levels, thus facilitating efficient and effective fire suppression.

The models are based on those factors which had the most influence on fireline construction rates for the data collected. Other factors may be more important in different circumstances. Fire managers should be aware of local conditions which may influence construction rates (such as extensive areas of rock on the surface in the volcanic plains of western Victoria) and adjust the suggested rates accordingly.

Most machine line construction from which the background data was derived was done late in the day or at night, when fire behaviour was significantly reduced, or where work was carried out at a distance from the fire edge. Fire managers should be aware of the possibility of both severe weather and consequent severe fire behaviour influencing machine construction rates during the hottest parts of the day.

The research found that the construction rate of hand trails was influenced by active fire nearby. The rate of construction of hand trails may be significantly reduced by active fire nearby, or even stopped if fire behaviour becomes too severe.

Hand trail construction rates

Figure 1. Rates of construction of hand trails under variable conditions of elevated fuel hazard and terrain

Figure 1 axes:
- y-axis: Firefighter construction rate (m/person/hr) — values 0, 10, 20, 30
- x-axis: Terrain class — Flat, 15 deg slope, 30 deg slope
- Lines labelled: Elevated fuel *low* or **moderate**; Elevated fuel **high**; Elevated fuel very **high** to **extreme**

Notes:

Construction rates: suggested average rate of construction of hand trail, expressed in metres per person per hour, achievable by a regular firefighting crew member during a working shift.

Fitness: add 1–2 m/person/hr to the predicted rate for rappel crews or others with a high level of fitness

Active fire close-by (threshold at 0.5 m high flame within 5 m): reduce the predicted rate by 25–30% with increasing flame height or closer fire. Construction may cease if fire behaviour is too severe.

Elevated fuel hazard: use *Overall Fuel Hazard Guide* (McCarthy *et al.* 1999)

Terrain: modelled as slope classes for simplicity. Although slope is the major factor, slope variation, position in the landscape, slope length and ground surface conditions also affect line construction rates.

Conversion table: fire area to fire perimeter

Table 1. Approximate perimeter of fires of a given area

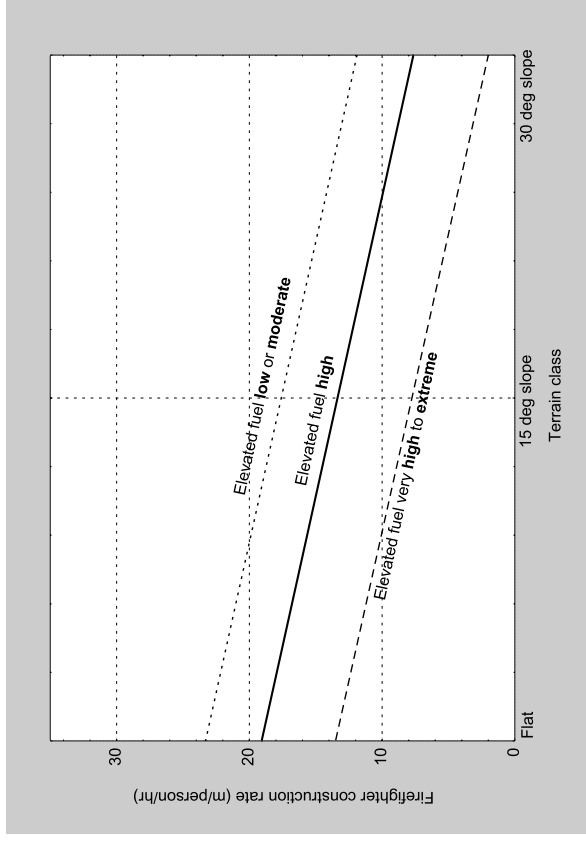| Fire area (ha)	Approximate perimeter (m)
0.5	250
1	360
2	500
5	800
10	1500
100	3600

Notes:

Perimeter measurement is based on a uniform, generally elliptical fire shape (as would be produced in response to wind and/or slope).

Convoluted fireline: Add 20–50% to the perimeter to account for twists and turns in the actual fireline if the distance or area cannot be measured by a vehicle odometer or other on-ground method. Similar additions should occur where mapping is done using the Global Positioning System or a helicopter-mounted Automatic Real-time Mapping System.

Estimating firefighter numbers

Table 2.   Estimated number of firefighters required for hand-line construction for given conditions of terrain, elevated fuel hazard and fireline length

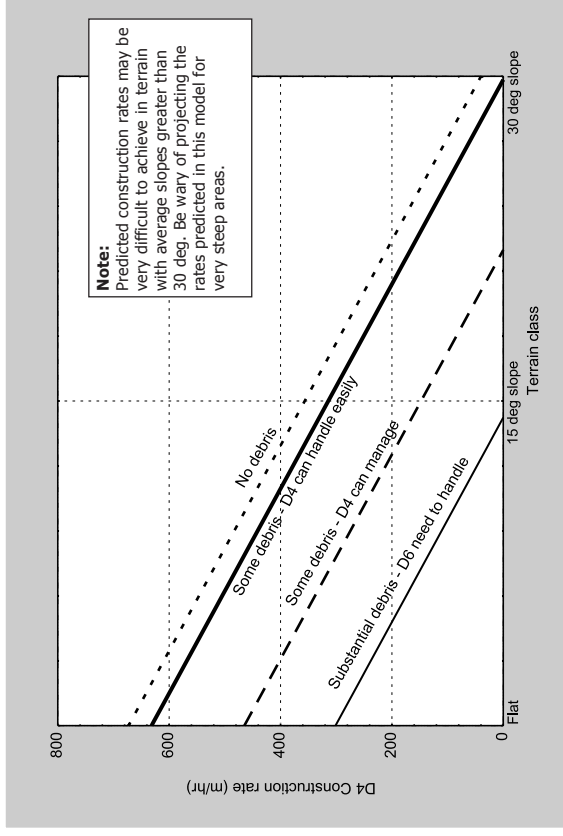|	Condition				Fireline length
Terrain	**15–30°** and/or	**10–15°** and/or	**0–10°** and/or	**0–10°** and/or	
Elevated fuel hazard	**Very high to Extreme**	**High**	**High**	**Low to Moderate**	
Likely construction rate (m/person/hr)	5–10	10–15	15–20	20–35	
Number of firefighters required	**12**	**6**	**5**	**4**	**250 m**
	25	**12**	**10**	**6**	**500 m**
	50	**25**	**20**	**12**	**1000 m**

Notes:

Firefighter numbers are based on an expected 4 hours of effective working time within an 8-hour shift and take account of tasks not directly related to fireline construction, such as walking in and out of the work-site, reconnaissance and rest periods.

Elevated fuel hazard: use *Overall Fuel Hazard Guide* (McCarthy *et al.* 1999)

D4 bulldozer line construction rates

Figure 2.   Rates of trail construction (single pass) by a D4 bulldozer under variable conditions of debris and terrain

Note:
Predicted construction rates may be very difficult to achieve in terrain with average slopes greater than 30 deg. Be wary of projecting the rates predicted in this model for very steep areas.

Notes:

Rates for down-slopes may sometimes be greater than that predicted for level ground where there is little debris, good visibility and good ground conditions.

Substantial debris includes standing live and dead trees, logs, heavy branches and taller elevated fuels.

Significant amounts of debris will slow a D4 to very low rates.

Very substantial amounts of debris: DO NOT use a D4 (even downhill); use a D6 or larger machine.

Operator experience is very important, especially with increasing debris and adverse terrain. Operators with limited experience (generally those with less than 10 years total, less than 5 years in forest situations or less than 10 forest fires attended) may reduce the rate by up to 50%.

Terrain class: modelled as slope classes for simplicity. Although slope is the major factor, slope variation, position in the landscape, slope length and ground surface conditions also affect line construction rates.

Combinations of firefighting resources

Table 3: Indicative minimum resource combinations required for various lengths of fireline

Fireline length (fire area)	Minimum resource combination
<1000 m (< 5 ha)	**First attack** **4–6 firefighters, 1–2 slip-ons, 1 D4 bulldozer (depending on circumstances)**
1000–2000 m (5–20 ha)	**Extended first attack** **10–15 firefighters, 3–6 slip-ons, 1 large tanker, 1 D4 and/or 1 D6 bulldozer**
2000+ m (>20 ha)	**20–50 firefighters for hand trail only fires (fireline length of up to 3000–4000 m total) supported by aircraft, or a reduced number of firefighters where D4 and/or D6+ bulldozers are in use.**

Note:

The combinations of resources in this table are based on the types of individual resources which were committed to fires of given fireline lengths. As a result they are indicative only but are included in this guide to assist fire managers to set minimum resource levels for containing similar lengths of fireline.

D6+ bulldozer line construction rates

Figure 3. Rates of trail construction (single pass) by a large bulldozer (D6–D9) under variable conditions of debris and slope
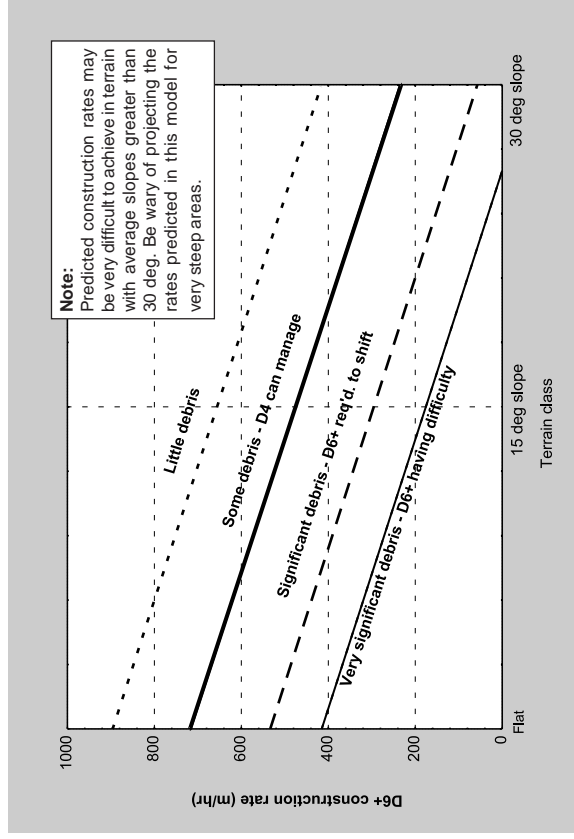
Note:
Predicted construction rates may be very difficult to achieve in terrain with average slopes greater than 30 deg. Be wary of projecting the rates predicted in this model for very steep areas.

(Chart axes: D6+ construction rate (m/hr) ranging 0–1000; Terrain class from Flat, 15 deg slope, 30 deg slope. Curves labelled: Little debris; Some debris - D4 can manage; Significant debris - D6+ req'd. to shift; Very significant debris - D6+ having difficulty)

Notes:

Rates for down-slopes may sometimes be greater than that predicted for level ground where there is little debris, good visibility and good ground conditions.

Substantial debris includes standing live and dead trees, logs, heavy branches and taller elevated fuels.

Rock can reduce line construction rates by a further 30–50%.

Scattered surface rock - reduce by 30%
Moderate surface and subsurface rock - reduce by 50%
Continuous surface rock - may not be trafficable

Operator experience: reduce rate by 10–30% for operators with limited experience (generally those with less than 10 years total, less than 5 years in forest situations or less than 10 forest fires attended).

Tanker fireline holding rates

Application of water or fire retardant is considered to be a method of only holding a fireline, not a method of fireline construction. A mineral earth fireline is generally considered necessary in Australian forest fuels.

Table 4.   Indicative fireline holding rates for a 4000-L tanker

	Condition			
Terrain	flat good access	flat good access	poorer access	poorer access
Wind	low	moderate	moderate	stronger
Bark hazard	low	mod	high	very high to extreme
Flame	<1 m high	1.5–2 m high	starting to climb trees	climbing most trees spotting 20–50 m from line
Fireline holding rate (m/hr)	1000–2000	500–1000	200–500	50–200

Notes:

Indicative fireline holding rates: Research into tanker fireline holding rates is limited for Australian conditions. The above rates are based on few observations and require further field checking.

Bark hazard: use *Overall Fuel Hazard Guide* (McCarthy *et al.* 1999)

Fireline access and fire behaviour would be the main influences on the holding rates for tankers. Poorer access comprises more debris or elevated fuel close to the line and steeper terrain.

Safety: Tankers should never work without access to safe anchor points, particularly in forest fuels, and should always "take 'the black' with them".

Firebomber fireline holding rates

Application of water or fire retardant is considered to be a method of only holding a fireline, not a method of fireline construction. A mineral earth fireline is considered necessary in Australian forest fuels.

Table 5.   Indicative fireline holding rates for a firebomber

Aircraft	**1400 L medium helicopter**	**1400 L medium helicopter**	**2500 L fixed-wing firebomber**	**2500 L fixed-wing firebomber**
Drop length (m)	30	30	70	70
Turnaround (minutes)	5	10–15	30	45–60
Fireline holding rate (m/hr)	360	120–180	140	70–100

Notes:

Indicative fireline holding rates: Research into firebomber fireline holding rates is limited for Australian conditions. The above rates are based on few observations and require further field checking.

Approximate firebomber holding rates can be derived from the average drop length for the particular type of firebomber and the turnaround time.

References

McCarthy, G J & Tolhurst, K G (1998). Effectiveness of Fire-fighting First Attack Operations, NRE Victoria 1991/92–1994/95. *Research Report* No. 45. Fire Management. Department of Natural Resources and Environment, Vic.

McCarthy, G J, Tolhurst, K G & Chatto, K (1999). Overall Fuel Hazard Guide (3rd Edition). *Research Report* No. 47. Fire Management. Department of Natural Resources and Environment and Centre for Forest Tree Technology, Vic.

McCarthy, G J, Tolhurst, K G & Wouters, M (2003.). Prediction of Firefighting Resources for Suppression Operations in Victoria's Parks and Forests. *Research Report* No. 56. Fire Management. Department of Sustainability and Environment, Vic.

McCarthy, G J (2003). Effectiveness of Aircraft Operations by the Department of Natural Resources and Environment and the Country Fire Authority 1997–98. *Research Report* No. 52. Fire Management. Department of Sustainability and Environment, Vic.

Further information

For further information and to provide feedback please contact Fire Management on 136 186 or visit www.dse.vic.gov.au/fires

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